The future of neutrino physics

Kendall McConnel
Columbia University

• Overview
• Unanswered neutrino questions
• Areas of neutrino research
• Ranking and Conclusion
Overview

• This class has spent 1 semester researching the different areas of neutrino physics
• In our final class, we discussed the major questions in neutrino physics we encountered and which experiments we think are most important
• Here’s what we’ve learned and our thoughts for the future…
Unanswered questions: fundamental

1. How many neutrino species? Are there sterile $\nu$?
2. Scale of neutrino mass and mass hierarchy
3. What is the neutrino mass/mixing matrix? Why is it so different from quarks?
4. CP violation in neutrino sector? Leptogenesis?
5. Dirac neutrinos? Majorana neutrinos?
Kinds of neutrinos

- Exp’ts at LEP show only 3 active flavors with mass < 45 GeV (from decay of the Z boson)
- They are all left handed
- Most Grand Unified Theories (GUTs) have extra particles which mix with the neutrino
  - It’s hard to build just a left handed one, especially if it’s massive
There are too many $\Delta m^2$'s for three neutrinos:

\[ \Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2 \]

- Non-interacting “sterile” neutrinos?
Scale of neutrino mass and mass hierarchy

- Currently, we know $\nu \sim < 1$ eV
- We have a lower limit on square root of $\Delta m^2$
- The electron ($m_e = 0.511$ MeV) is $\sim 500,000$ times bigger than the neutrinos, why?
- What is the order of the mass eigenstates? Is there an overall offset?

\[
\begin{align*}
\Delta m_{23}^2 & \quad \nu_3 \quad \leftrightarrow \text{Like quarks?} \quad \nu_3 \quad \Delta m_{23}^2 \\
\Delta m_{12}^2 & \quad \nu_2 \quad \text{Not like quarks?} \quad \nu_2 \quad \Delta m_{12}^2 \\
\nu_1 & \quad \rightarrow \quad \nu_1
\end{align*}
\]
Neutrino mass/mixing matrix

\[ \begin{pmatrix} v_e & v_\mu & v_\tau \\ & & \\ & & \end{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} \]

- All terms are big, except for \( U_{e3} = \sin \theta_{13} e^{i\delta} \); how small is \( \theta_{13} \)?
  - \( \theta_{13} \) is mixing angle, \( \delta \) is possibly CP violating phase
- Quark matrix is big only on diagonal
CP violation?

• A symmetry just means nature does not distinguish
  – C: charge, $\nu \rightarrow \text{anti-}\nu$
  – P: parity, $\nu_{\text{Left}} \rightarrow \nu_{\text{Right}}$

• CP violation in neutrinos would mean that the probability of oscillation for neutrinos is different than anti-neutrinos

• CP violation in leptons could be a reason why we see matter/antimatter asymmetry in the universe
  – Leptogenesis (Boris, care to elaborate?)

• CPT violation would mean the mass hierarchy of neutrinos would be different from anti-neutrinos
Majorana neutrinos

• The difference between particle & antiparticle is usually electric charge. (particles move one way in a B-field, antiparticles the other)

• But neutrinos have no charge with which we can tell a difference If neutrinos are Majorana particles, then neutrinos are their own antiparticles, and, in principle, they can annihilate...

Neutrinoless Double $\beta$ decay

$\nu = \text{anti-}\nu$

Majorana neutrinos are a feature of a lot of GUTs
Unanswered questions: in astrophysics

Use neutrinos to as probes of universe:

6. High energy neutrino physics
   • Origin of highest energy cosmic rays?
   • New (TeV scale) physics?

7. Find new astrophysical sources (e.g AGN)

8. Learn more about supernova (DSNB)

9. See early universe with relic ν (CNB)
   • At the moment, no experiment. Ideas?
Areas of neutrino research

• Solar neutrinos
• Atmospheric neutrinos
• Long Baseline experiments
• Short Baseline experiments
• Reactor neutrinos
• Neutrino-less beta decay
• Neutrinos from space
• Neutrino factory (R&D)
Detection

• Neutrino enters detector, interacts and a charged particle leaves
  – Indirectly observe neutrino by
    I. Calorimeter detectors
    II. Cerenkov light
    III. Radiochemical detectors
    IV. Liquid Argon/noble gas detectors
Calorimeter Detectors

• Consists of slabs of “target” material (steel, in MINOS) alternated with “active” material (like solid scintillator and fibers)

• Neutrino enters, interacts in target, interaction products (like muon or electron) are read out by active material
Cerenkov Detector

- Neutrino interacts in tank (filled with oil, liquid scintillator, water or heavy water)
- Charged particle moving faster than the speed of light in that medium produces a “light boom”, which is read out by PMTs
Radiochemical detectors

• Detector is filled with a chemical (Homestake contained Cl)

• Neutrino interacts and changes Cl into Ar:

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \]

• After some period of time, the atoms that interacted with the neutrinos are collected (via “bubbling” gas in tank) and counted
Liquid Argon TPC

1. Passing charged particles produce ionization electrons
2. Electrons drift to wire planes
3. Has very good resolution
Solar neutrinos

Electron neutrinos come from different reactions in the sun

- Mainly from pp “chains”
  \[ p + p \rightarrow H + e^+ + \nu_e \] and \[ Be + e^- \rightarrow Li + \nu_e \]
- Are of typical energies of \( \sim 1-10 \) MeV

These are measured by a host of experiments:
- Homestake, SAGE, GALLEX, Super-Kamiokande (Super-K) and most notably, SNO.
Solar neutrinos

• Only $\sim 1/3$-$2/3$ of the expected $\nu_e$ are observed

• Is this oscillation? Yes! SNO confirmed $\nu_e$ flux, Kamland reproduced effect with reactor $\nu_e$
Atmospheric neutrinos

ν are also produced in the atmosphere (<100 MeV)

\[ p + N \rightarrow \pi \rightarrow \mu + \nu_{\mu} \]

\[ \mu \rightarrow \nu_{\mu} + e^- + \nu_e \rightarrow \text{Expect 2 } \nu_{\mu} \text{ to 1 } \nu_e \]

Super-K sees a deficit of ν_μ and expected ν_\text{e}; oscillation!?
Oscillation!!

- We now have an answer for the solar neutrino and the atmospheric problem… but now we have more questions
- Solar and atmospheric neutrino physics have opened the door for current accelerator neutrino physics (short and long baseline experiments)
Long Baseline Experiments

• Accelerators produce 1-20 GeV $\nu_\mu$ that are seen at a distant (250km-733km) detector
• Measures oscillations at atmospheric L/E~1/$\Delta m^2$
• Currently, K2K, MINOS and soon CNGS, JPARC
• Future experiments include
  – off axis beams (narrower $\nu$ energy spread, but lose rate)
  – superbeams (low E, high intensity beams with less background of $\nu_e$ off axis)
Long Baseline Exp’ts (cont’d)

• Has great physics potential (CP violation, mass hierarchy, mixing matrix)
• Accelerator is reusable for future exp’ts
• Costly in time (~8 years) and money (min ~500 million US$) if better than existing exp’ts
• Depends on $\theta_{13}$ and accelerators p.o.t.

➢ Wait for reactor experiments to establish $\theta_{13}$ and do useful R&D/planning till then
  
  If $\theta_{13}$ is small, Liquid argon detector might be needed
Short Baseline Experiments

• Similar physics to long baseline exp’ts, just look at a different L/E or $1/\Delta m^2$

• MiniBooNE
  – Third $\Delta m^2$ observed by LSND needs to be confirmed or disproved

• HARP
  – Better measurement of pion cross section for neutrino production at different energies

• MINErVA and FINeSSE
  – Additional detectors for MINOS and MiniBooNE
  – improves particle ID, measure n cross section, increase understanding of backgrounds and improves oscillation results
Short Baseline Experiments

- Possible CPT violation (no signal in $\nu$, signal in anti-$\nu$) and sterile $\nu$ (signal in $\nu$)
- Establishes not well known $\nu$ cross sections
- MINErVA and FINeSSE improve results their parent experiment
- All are cheap (~4-6 million US$)
  - Provides important checks and information for future exp’ts
Reactor Experiments

• Nearby detectors observe isotropic anti-\(\nu_e\) from reactors (~1-10MeV)
• Measure not-well-known mixing angle (\(\theta_{13}\))
• Expt’s include
  – Kamland (solar \(\Delta m^2\))
  – Paulo Verde and CHOOZ (atm \(\Delta m^2\))
  – Unnamed future exp’ts
• Cheap (~25-50 mil US$) but not reusable detectors
• Provides important measurement of \(\theta_{13}\) (If \(\theta_{13}\) too small, then can’t measure with long baseline exp’t)
  ➢ Important to do now and do fast
Neutrinoless beta decay ($0\nu\beta\beta$)

• Large, very sensitive detector sits underground and waits for such a decay
  – Backgrounds are from $2\nu\beta\beta$ rate, and especially any radioactive material

• Current expt’s:
  – Heidelberg-Moscow ran for ~10 yrs, claims detection… but has not convinced the community

• Future expt’s:
  – EXO, GENIUS, MAJORANA, and more!
Neutrinoless double beta decay

• Klapdor-Kleingrothaus et al released a paper in 2001 claiming that they had detected neutrinoless double beta decay, based on this graph
\( \nu \beta \beta \)

- Can establish if \( \nu \) is Dirac or Majorana (essential in most GUTs)
- Detectors are large, expensive and have difficult backgrounds
- Feasibility of this measurement has not been well established

➢ Investigate first
  - if it is proven it works and isn’t too expensive then fund
Neutrino astrophysics

• **AMANDA/IceCUBE**
  – Giant Cerenkov detector in Antarctic ice
  – acts as a “neutrino telescope”

• **SNEWS**
  – Network of neutrino detectors around the world
  – Directs astronomers to supernovae early using neutrinos that come before light does

• **GADZOOKS**
  – Stands for: Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!
  – Dump GdCl$_3$ into Super-K to improve observational capabilities of supernova $\nu$
Neutrino astrophysics (cont’d)

• Vast possibilities in astrophysics
  – Supernovae (DSNB and early detection)
  – origin of highest energy cosmic rays
  – AGNs and other exotic sources

• Risky
  – what if there is no supernova? no new physics?

• Relatively cheap for potential
  – IceCube ~100 million US$, other much less ~500,000$

➤ Worth it in short term
  – Provided GdCl$_3$ is safe in Super-K (and GADZOOKS changes the name)
Neutrino factory

Intense proton source produces pions which decay to muons

The muons are bunched, cooled and put in rings and decay to neutrinos

=> Intense neutrino source!
Neutrino factory

- Has the ability to answer many of the outstanding questions with high $\nu$ fluxes
- Other (non-$\nu$) physics uses (muon colliders)
- But we can’t build one yet!
  - Current R&D projects are MICE and MUCOOL
  - Difficulties in controlling a muon beam
    - Hard to cool muons, they decay quickly
    - Muons are difficult to collimate

- Long term goal: continue R&D
Ranking and Conclusion

- Atmospheric and solar sector have paved the way for current experiments
- Funding to:
  I. Reactors
  II. Astrophysics projects
  III. Short-baseline experiments
  IV. R&D on (useful) long baseline technology
- Investigate neutrino-less beta decay
- For the long term, invest in neutrino factories
Choices (I)

- Reactors
  - Knowing $\theta_{13}$ gives the long baseline experiments important information in designing the next generation project (500 million with the wrong detector?)

- Astrophysics projects
  I. SNEWS and GADZOOKS provide more information on supernovae, and are very cheap
  II. IceCUBE is not cheap, but we can’t explore TeV scale on earth for that price
Choices (II)

- Short Baseline
  I. Cheap and improved (or new) physics
  II. Close (or open) doors on LSND

- R&D on long baseline technology
  I. Liquid Argon detectors are the next kind of detectors, worth research
  II. Any long term project is always worth taking time to think out
Choices (III)

• Investigate neutrino-less beta decay
  – Important physics question, but is experiment possible?
• For the long term, invest in neutrino factories
  – Next generation for not only neutrinos, but colliders in general
## Timeline

<table>
<thead>
<tr>
<th>Now</th>
<th>Near future</th>
<th>Far future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactors</td>
<td>Long baseline</td>
<td>Neutrino Factories</td>
</tr>
<tr>
<td>Short baseline</td>
<td>$0\nu\beta\beta$?</td>
<td></td>
</tr>
<tr>
<td>$\nu$ Astrophysics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R&amp;D on LBL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>